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High-gain PDMS-magnetite zero refractive index metamaterial antenna for Vehicle-to-Vehicle communications

Noorlindawaty Md. Jizat[1], Nazihah Ahmad[2], Zubaida Yusoff[3], Mohd Faizal Jamlos[4]
[1,2,3]Faculty of Engineering, Multimedia University, Persiaran Multimedia, 63100, Cyberjaya, Selangor, Malaysia
[4]Advanced Communication Engineering Centre (ACE), School of Computer and Communication Engineering, Universiti Malaysia Perlis, Malaysia

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ABSTRACT

This paper presents the simulation design of a high-gain antenna using zero refractive index fishnet metamaterial (MTM) perforated on PDMS-Magnetite substrate for Vehicle-to-Vehicle (V2V) communications. In order to design the MTM, magnetite nanoparticles, 10-nm iron oxide (Fe_3O_4) are dispersed into polydimethylsiloxane (PDMS) matrix. Subsequently, the unit cell is designed by removing the circular hole with radius of 3.69 mm on the PDMS-Magnetite substrate layer and arranged in 5×5 array fishnet configuration. This optimized MTM is inserted between the antenna design and pure PDMS substrate to improve the gain. The characteristic of the respective unit-cell is investigated to operate at 5.9 GHz and the effectiveness of MTM is performed by comparing the antenna performance with and without MTM. The unique characteristics of zero refractive index transform the diverging wave into plane wave for perfectly parallel wave impact on the design to improve the directivity and gain of the antenna. The proposed MTM into design improves the antenna gain to 7.36 dB without having to compromise other antenna parameters of return loss, Voltage Standing Wave Ratio (VSWR), gain, directivity, efficiency, current distribution, radiation pattern and bandwidth. These advantages has made proposed antenna as a suitable candidate for V2V in Dedicated Short Range Communication (DSRC) application since high-gain directional antenna is required to increase the sensitivity towards signals coming from certain direction.

Corresponding Author:

Noorlindawaty Md Jizat,
Faculty of Engineering, Multimedia University,
Persiaran Multimedia, 63100, Cyberjaya, Selangor, Malaysia.
Email: noorlindawaty.jizat@mmu.edu.my

1. INTRODUCTION

Vehicle-to-Vehicle (V2V) Communication is a wireless system based on IEEE 802.11p protocol where few information exchanges between host and neighboring vehicles within Dedicated Short Range Communication system (DSRC) frequency of 5.875–5.925 GHz. Previously**,** extensive research has been explored on antenna design for vehicle to vehicle at DSRC application [1-3]. However, most of this antenna has constraint in the gain and directivity which limit the application. In order to overcome this limitation, MTM is identified as one of the breakthrough technology to improve the RF performance [4-8].

Advent of MTM opens new possibility for the researcher to create a new frontier of structure with artificial properties based on permittivity, permeability and refractive index value by modifying the shape, size, and configurations of the unit cells. The idea of MTM is initiated by Russian theorist Veselago [9] when he proposed artificial material with negative index refraction. Since then many researchers have been developing and investigating this unique MTM characteristic including Smith who performs microwave experiments to build the MTM prototype in year 2000 [10]. Although many types of MTM has been used to improve microwave device performance [11, 12], the focus is gradually divert to the zero refractive index due to the unique properties of manipulating the diverging wave into plane wave for direct emission and gain enhancement. Polymeric-based MTM is the latest trend for substrate design structure [13-16] due to attractive properties such as low permittivity, low loss, flexible, possess thermal stability, homogeneously dispersed, and ease of modification. Due to these extraordinary properties, researchers have discovered artificial polymeric magnetic loading as MTM to improve the antenna performance [17-19].

In this project, PDMS- magnetite (PDMS- Fe_3O_4) are used to form the artificial polymeric magnetic MTM due to high profile of piezoelectric properties, and have natural magneto dielectric materials with low magnetic losses. The zero refractive index fishnet MTM is perforated on the PDMS-Magnetite and inserted between the antenna and pure PDMS substrate. Significantly, the gain of the proposed antenna improved by 3.08 dB (58%) compared to the design without MTM. In addition, promising results of return loss, VSWR, gain, directivity, efficiency, current distribution, radiation pattern and bandwidth of the antenna are obtained from the proposed design.

2. ZERO REFRACTIVE INDEX MTM

Theoretically, Snell's law ($n_1 \sin \theta_1 = n_2 \sin\theta_2$) indicates the angle of refraction (θ_2) will be close to zero independent to angle of incidence (θ_1), if the ray is emitted from inside the zero refractive-index ($n_1=0$) into free space ($n_2>0$). Thus, the refracted rays will be normal to the interface, $n=\pm\sqrt{\varepsilon\mu}$. These unique phenomena controlling the signal emission resulted from the dispersion characteristics of the MTM composite transmission line. In order to achieve zero refractive index properties, PDMS-Magnetite MTM unit cell is designed.

2.1. Metamaterial Design

Response of each unit cell is predetermined prior to the antenna design. In order to retrieve constitutive parameters of MTM, Nicholson Ross Weir (NRW) technique is used. The retrieval algorithm is used in Matlab to produce refractive index, n, permittivity, ε and permeability, μ of the unit cell [20-21]. The constitutive effective parameters that depend on the reflection coefficient, S_{11} and transmission, S_{21} value of the unit cell are calculated from (1) till (5).

$$z = \sqrt{\frac{(1+S_{11})^2 - S_{21}^{\;2}}{(1-S_{11})^2 - S_{21}^{\;2}}} \tag{1}$$

$$e^{(jnk_0 d)} = A \pm j\sqrt{(1-A^2)} \tag{2}$$

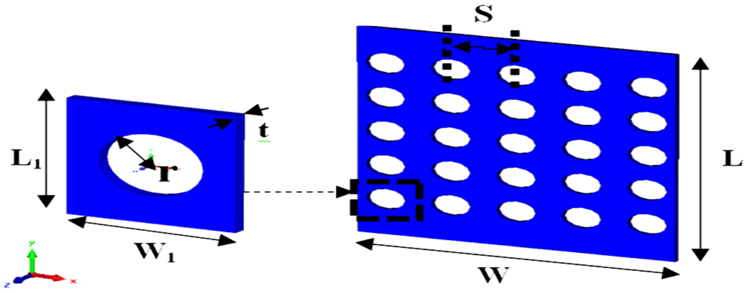
$$A = \frac{(1-S_{11}^{\;2} + S_{21}^{\;2})}{2S_{21}} \tag{3}$$

$$\varepsilon = n/z \tag{4}$$

$$\mu = n \times z \tag{5}$$

where: z =impedance
ε =Relative effective permittivity and μ=Permeability
n =Refractive index
k_0=Wavenumber
d=Slab thickness

Figure 1(a) illustrates the geometrical parameters and dimension detailed of the unit cell with the size of 0.23 $\lambda_0 \times 0.27\ \lambda_0$. As shown in Figure 1(b), the fishnet MTM with circular hole was perforated with radius of 3.69 mm in the PDMS-Magnetite substrate with thickness of 1mm. The PDMS-Magnetite hole was arranged in 5×5 periodically array configuration and spacing, S of 12.29 mm between them. The detailed parameter was tabulated in Table 1. The proposed unit cell array was placed in an electric boundary in the x-axis, magnetic boundary in the y-axis while the two open ports were in the z-direction.



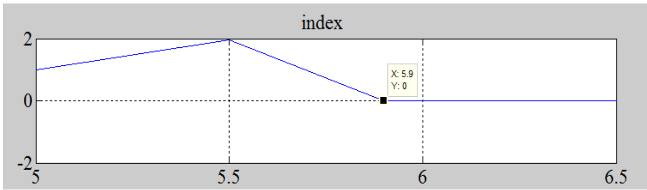
(a) (b)

Figure 1. Front view (a) unit cell and (b) metamaterial cells

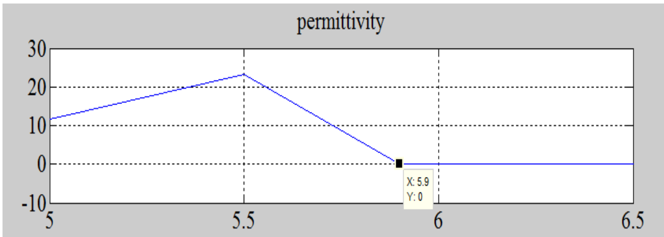
Table 1. Design Parameters of the Metamaterial Unit Cell

Parameters	Length (mm)
W	59.70
L	74.64
W_1	12.00
L_1	14.00
t	1.00
r	3.69
S	12.29

The unit cell is analyzed using computer simulation technology (CST) software. This value is then inserted in the Nicholson Ross Weir (NRW) programming and simulated using Matlab algorithm. Optimizing circular hole of the proposed MTM and configuration between the antenna layers that produce zero refractive index, permittivity and permeability at 5.9 GHz is demonstrated in Figure 2(a)-(c).



(a)



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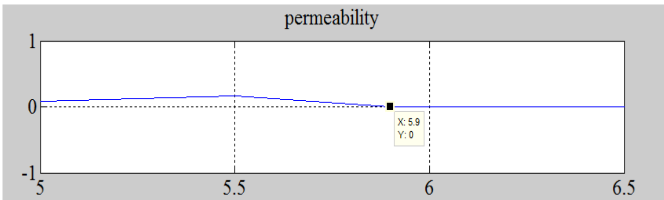

(c)

Figure 2. Unit cell response in *z*-axis wave propagation for (a) refractive index (b) permittivity index (c) permeability index

3. MICROSTRIP PATCH ANTENNA

The proposed MTM is inserted between pure PDMS substrate, patch antenna and ground as shown in Figure 3. The pure PDMS has thickness of 0.5 mm and dielectric constant of 2.7 while ground is made from copper with thickness of 0.035mm. The dimension of the patch is optimized to 40 mm× 37.5 mm in size while ground plane, PDMS substrate and PDMS-Magnetite substrate having same dimension of 59.7 mm × 74.64 mm. A 50 Ω coaxial probe used to feed the antenna with the dimension of 7.5 mm×20 mm. The optimized configuration of the proposed antenna with the MTM is performed to obtain highest gain in the z-direction.

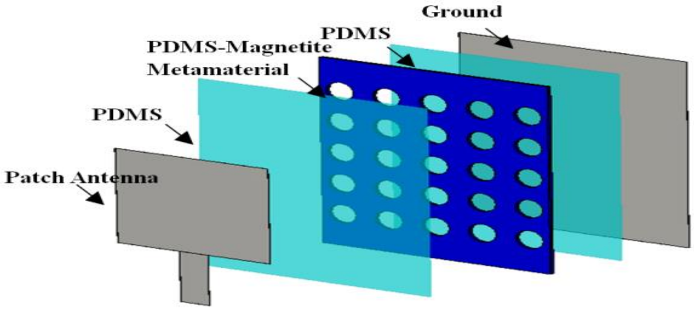

Figure 3. Architecture of the proposed MTM antenna

4. RESULTS AND DISCUSSION

The antenna's performance in terms of return loss indicate good reflection coefficient of -13.52 dB at 5.9 GHz as shown in Figure 4. Computer Simulation Technology (CST) was used to simulate the antenna performances and detailed data are tabulated in Table 2. The proposed antenna demonstrates 10-dB impedance bandwidth of 170MHz which fulfill the DSRC requirement bandwidth (5.875–5.925 GHz).The proposed antenna impedance matched with the transmission line and effectively delivering the energy indicated with the Voltage Standing Wave Ratio, VSWR of 1.53.

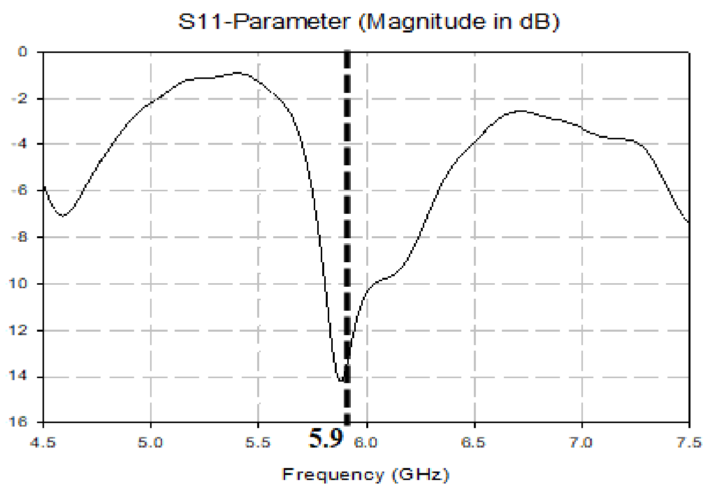

Figure 4. Return loss, S_{11}

Table 2. Proposed antenna simulation performances

Antenna Performance	With MTM	Without MTM
S_{11}(dB)	-13.52	-11.43
VSWR	1.53	1.73
Gain(dB)	7.36	4.28
Directivity(dB)	7.35	4.28
Efficiency (%)	95	95

The simulated current distribution agrees well with the 2D and 3D radiation pattern as illustrated in Figure 5 and Figure 6. As such, both values denote high gain of 7.36 dB, high directivity value of 7.35 dB and 95% radiation efficiency. The radiation pattern is illustrated for both E-plane and H plane correspondingly with the adjusted cross sectional of φ=90° and θ=90°. The maximum gain results for the patch antenna with the inclusion of proposed MTM improved to 7.36 dB making it a suitable candidate for high gain and high directivity that is compatible to be used for vehicle to vehicle Dedicated Short Range Communication system (DSRC) application.

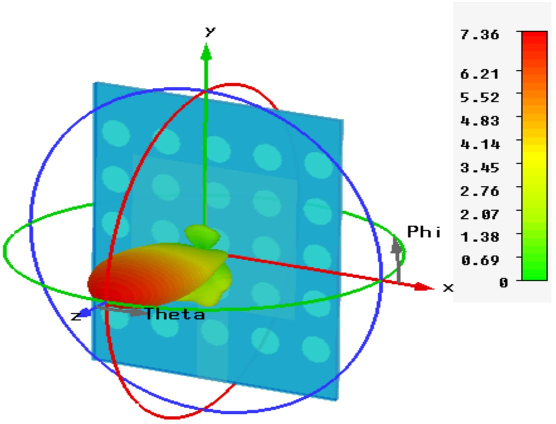

Figure 5. Simulated 3D gain radiation pattern of the proposed antenna

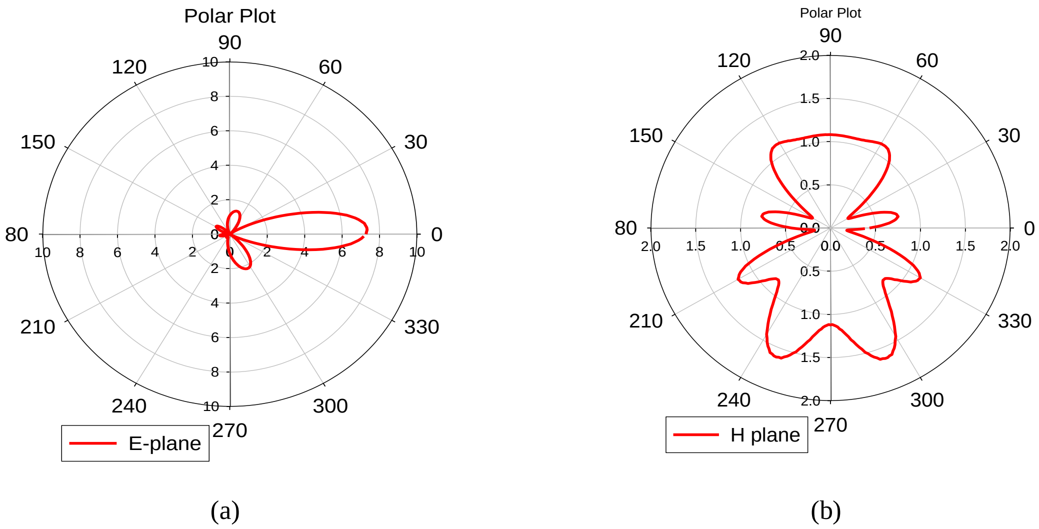

Figure 6. Polar plot of the proposed MTM antenna (a) E-plane (b) H-plane

Surface current distribution in Figure 7 illustrates that the flowing current over the PDMS-Magnetite metamaterial unit cell surface is stronger along the circular hole of PDMS-magnetite fishnet metamaterial. The highest intensity (red) corresponds to 35.5 A/m and the lowest intensity (blue) corresponds to 0 A/m.

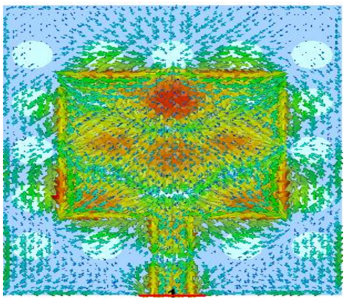

Figure 7. Current distribution at the resonance frequency

5. CONCLUSION

In conclusion, 5×5 circular hole PDMS-Magnetite MTM has been designed as zero refractive index and inserted as substrate between the antenna designs to produce high-gain and directional performance. While existing antenna has limited performance, artificial polymeric magnetic MTM is introduced to create highly profile high-gain antenna to increase the signal strength. The refractive index of the unit cell at 5.9 GHz has zero refractive index, whereby the wave passing through the proposed medium will be orthogonal to the surface and significantly improve the antenna's gain. The promising performance of the proposed antenna design is to be integrated for vehicle- to- vehicle communication system in DSRC application since high-gain directional antenna is required to increase the sensitivity towards signals coming from certain direction.

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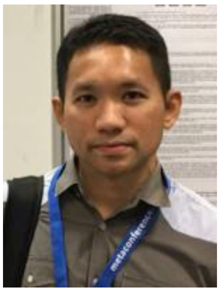
BIOGRAPHIES OF AUTHORS

Noorlindawaty Md. Jizat obtained her Bachelor of Electrical Engineering (Telecommunication) degree from Universiti Teknologi Malaysia in 2008. She then received her Master from Universiti Teknologi Malaysia. She worked as an R & D Engineer at Panasonic System Network Malaysia till 2012. Her research interests cover the field of Beamforming network, Smart Antenna, Switching Network. She is currently working as a Lecturer at Faculty of Engineering, Multimedia University (MMU), Cyberjaya, Malaysia.

Nazihah Ahmad graduated with bachelor degree in Mechatronics Engineering (Hons) from International Islamic University in 2007. She was awarded a master in Biomedical Engineering in 2012. Her research interests are various fields of Biomedical engineering and social science. She is currently working as a Lecturer at the Faculty of Engineering, Multimedia University, Cyberjaya, Malaysia.

Zubaida Yusoff received her B.Sc. in Electrical and Computer Engineering (cum laude with distinction) and M.Sc. in Electrical Engineering from The Ohio State University, USA in 2000 and 2002 respectively. She worked with Telekom Malaysia International Network Operation in 2002 before she joined Multimedia University, Malaysia as a Lecturer in 2004. She continued her studies at Cardiff University, Wales, UK in 2008 and received Ph.D degree in 2012. She is currently resumes her job as a Senior Lecturer at Multimedia University. Her current research interest is in the area of Analog/Mixed Signal Circuit Design and RF Power Amplifier System.



Mohd Faizal Jamlos receives his Ph.D in Electrical Engineering, UTM, M.Eng (Electrical-Electronic), Adelaide University and B.Eng (Computer Engineering) from UniMAP. His research interest in Antenna design, Microwave Security System, Intelligent Microwave Transportation System, Microwave Biomedical Instrumentations. He is currently Associate Professor in School of Computer and Communication Engineering University Malaysia Perlis, Malaysia.